Massachusetts Institute of Technology
Instrumentation Laboratory
Cambridge, Massachusetts 02142

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To: Instrumentation Laboratory
From: D. G. Hoag
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Subject: Report on Apollo 8

In an historic first, this country sent men to the moon in Apollo 8 with MIT's Guidance, Navigation, and Control System sharing in a remarkable performance of Apollo spacecraft, flight crew, and ground operations.

The liftoff of Saturn launch vehicle 503 occurred 7:50 am EST on 21 December 1968, and injected astronauts Borman, Lovell, and Anders in Spacecraft 103 towards the moon which they orbited 10 times on Christmas Eve before returning to recovery in the Pacific on the morning of 27 December after a 147 hour flight.

Few problems and superb performance were experienced with the GN&C. Both the inertial subsystem and the computer were left operating the whole mission. The crew, using the optics, made periodic IMU alignment checks and many navigation measurements. For long periods of time the navigation state vector was kept up to date only by the on-board measurements. In a different location in the computer an MSFN ground tracking determined state vector was held and renewed periodically by up-telemetry. Although these two had no significant difference, mission control overwrote the on-board navigation data with the MSFN values before each maneuver so that they would be accomplished on the basis of the ground tracking initial conditions. All major maneuvers and entry were guided and controlled automatically by our system and monitored by the crew.

The inertial measurement unit was given two major realignments by crew star sightings to set up new preferred orientations, first for lunar operations and then for earth return. Many star sighting alignment corrections were performed, typically several hours apart and requiring correction angles of the order of only

a few hundredths of a degree. These realignments gave the data required to check IMU drift for each of the three gyros. The drift was uniformly consistent and matched the low values measured on the ground before launch. Likewise, accelerometer output during free fall gave a most satisfying measure of accelerometer bias stability. Dr. Draper's prognosis of superior inertial component performance in space has surely been demonstrated.

The mission plan for translunar navigation was to (1) confirm the on-board navigation capability, (2) confirm independently that the lunar arrival would be safe, and (3) to calibrate Captain Lovell's use of the earth horizon as a navigation target. Loss of communication would require on-board sightings alone to be used on the return to assure safe atmospheric entry.

The crew were aided in optics star acquisition by the automatic pointing feature of the IMU realignment program (P52). Likewise, automatic acquisition pointing of both landmark and star lines in the midcourse navigation program (P23) allowed Lovell to make quickly each of over 200 cislunar earth and lunar horizon sextant navigation sightings. MIT had preselected the best visible stars of the 37 in the computer's star catalog for navigation use. His superposition of the star in the sextant on the earth's illuminated limb was at a remarkably uniform altitude above sea level but about 8 kilometers lower than he selected as his subjective target a few weeks before the flight on the MIT simulator. This horizon bias was determined independently during the first part of the outbound leg by both MSC and MIT. His performance with the optics was excellent even when fatigue was otherwise evident. The consistency of all his "marks", except when the spacecraft was close to the target body, was rarely greater than the 10 arc second quantization size of the sextant trunnion angle readout.

The sextant data were processed in the flight computer with Dr. Battin's recursive estimation formulation and as they approached the moon this on-board navigation was for all intents the same as the MSFN ground tracking data. There was no reason, then, why they couldn't have used this on-board state vector to initialize the lunar orbit insertion maneuver. This would have been an impressive demonstration of the actual complete on-board capability. However, the flight plan specified a state vector update before lunar orbit insertion, and the Flight Controller chose to proceed with this plan, since there was no overriding argument for deviation.

The Saturn guided translunar injection errors and the subsequent manual maneuvers needed to separate from a persistent SIVB they couldn't seem to shake required a 25 ft/sec correction using the main SPS engine. This was made at

11 hours into the mission. The next two scheduled midcourse corrections were not necessary and were not made. The final translunar midcourse correction, made at 8 hours before lunar orbit insertion was only 3 ft/sec using the small reaction control jets.

The anxious wait for the spacecraft to make its first reappearance from in back of the moon on Christmas Eve following the out-of-sight lunar orbit insertion maneuver was rewarded with the report from the crew that the on-board computer gave their orbit as 60.5 by 169.1 nautical miles altitude ... so close to the planned 60 by 170 orbit that the unavoidable emotional tension was broken with unrestrained cheers. About 25 minutes later the ground reported that radar tracking had established an orbit comparing favorably with the on-board data. Two orbits later, after the circularization maneuver, the spacecraft emerged in sight with the satisfying report of a 60.6 by 60.7 nautical mile lunar orbit.

During lunar orbit, Lovell used the sextant and scanning telescope to track known lunar reference points, including potential landing sites. These data were telemetered to earth for post flight analysis.

The critical 3500 ft/sec return-to-earth maneuver early Christmas morning was guided so accurately that only a single 5 ft/sec correction, made five hours later, was required to hit the center of the atmospheric entry corridor 42 hours later.

Our MIT teams of experts at Florida, Houston, and Cambridge who provided support to mission control, were constantly monitoring and checking the progress of the flight and were called upon several times for consultation and recommendations.

A false alarm hardware problem which acquired the nickname "travelling trunnion" was manifest by a transient change of the optics trunnion indication in the computer and was associated with the procedure of starting optical sightings. In each case it occured, Lovell merely rezeroed and proceeded without hesitation or concern. With the limited data we had available it took some ingenious sleuthing by our team to be able to certify confidently continued safe use of the optics. The curious action of the trunnion indication was finally understood completely only after discussing with Lovell the details of the procedures he used. The phenomenon involves the way in which the optics behave with power off in the free-fall environment of space flight. There was no failure or degradation of any GN&C hardware in the mission.

Considering the huge workload of GN&C use, which successfully exercised all functions except rendezvous, it is surprising so few operational problems were experienced in this flight. In the several cases which did occur, the computer gave proper alarm indication and the astronauts were able to recover without help from the ground. In three cases of question, MIT examined the contents of the erasable memory and was able to verify that corrections did not need to be telemetered up.

On the way back from the moon the on-board and the ground tracking navigation were essentially identical. Both were well within the tolerance needed for entry control. Lovell was still using the same altitude horizon for his P23 navigation he used on the way out. Our system controlled automatically the 36, 200 ft/sec atmospheric entry to a spectacular landing next to the recovery carrier. The ship has reported splashdown coordinates within a third of a mile of the target coordinates in the flight computer.

This historic milestone "reach for the moon" was watched with fascination by a world which will never again view our natural satellite as so remote.

Although the triumph of Apollo 8 belongs to all mankind, to the least of us on the Apollo team belongs the pride of having participated. The Instrumentation Laboratory's substantial contribution is in the record.

D. G. Hoag

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